

Progress Report Number 2

NASA Grant Number: NAG5-12859

Grant Title:

**WAVE-PARTICLE INTERACTIONS AS A DRIVING MECHANISM
FOR THE SOLAR WIND**

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Submitted to

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NASA Headquarters, Code SS

Washington, DC 20546-0001

November 8, 2004

Wave-Particle Interactions as a Driving Mechanism for the Solar Wind

I. Synopsis

Our research has been focusing on a highly experimentally relevant issue: intermittency of the fluctuating fields in outflowing plasmas. We have contributed to both the theoretical and experimental research of the topic. In particular, we have developed a theoretical model and data analyzing programs to examine the issue of intermittency in space plasma outflows, including the solar wind. As fluctuating electric fields in the solar wind are likely to provide a heating and acceleration mechanism for the ions, our studies of the intermittency in turbulence in space plasma outflows help us toward achieving the goal of comparing major physical mechanisms that contribute to the driving of the fast solar wind.

Our new theoretical model extends the utilities of our global hybrid model, which has allowed us to follow the kinetic evolution of the particle distributions along an inhomogeneous field line while the particles are subjected to various physical mechanisms [Tam and Chang, 1999a,b; 2001]. The physical effects that were considered in the global hybrid model included wave-particle interactions, an ambipolar electric field that was consistent with the particle distributions themselves, and Coulomb collisions. With an earlier version of the global hybrid model, we examined the overall impact on the solar wind flow due to the combination of these physical effects. In particular, we studied the combined effects of two major mechanisms that had been proposed as the drivers of the fast solar wind: (1) velocity filtration effect due to suprathermal electrons; (2) ion cyclotron resonance. Since the approval of this research grant, we have updated the model such that the effects due to these two driving mechanisms can be examined separately, thereby allowing us to compare their contributions to the acceleration of the solar wind. In the next section, we shall demonstrate that the velocity filtration effect is rather insignificant in comparison with that due to ion cyclotron resonance.

The global hybrid model provides the framework of our new simulation model, which enables our theoretical studies to keep up with recent experimental findings. Recent analyses of solar wind data have indicated that the broadband magnetic field fluctuations exhibit intermittency [Bruno *et al.*, 2001; Sorriso-Valvo *et al.*, 1999]. In fact, experimental data in various space plasmas, including the auroral region, have indicated that broadband fluctuations in space are generally intermittent in nature. Our new simulation model incorporates the effect of broadband intermittent fluctuations on the acceleration of an outflowing plasma. We have successfully tested this global evolutionary model with intermittent fluctuations by applying it to the auroral region. Instead of the solar wind, the auroral region was chosen for the preliminary study because of its smaller overall size. Note that the ion acceleration in the aurora, like the solar wind, is a multiscale phenomenon. But the smaller overall size of the aurora allowed us to save a lot of computational resources during the testing phase for our new intermittency model. Our preliminary calculations based on the model have shown that broadband intermittent fluctuations may provide the heating that leads to the conic events observed in the auroral

region (Section III). We expect our model to be fully applicable to the broadband fluctuations in the solar wind, which, as discussed above, is also intermittent in nature.

In order for our theoretical studies to be relevant to the real conditions in space plasma outflows, we have to rely on experimental data to provide the guideline for the inputs of our intermittency model. However, as far as we realize, there has yet to be a publication in space physics on the intermittency of turbulent electric fields in any outflowing plasma. Thus, we have proceeded to extend our research on intermittent turbulence by performing analyses on experimental data of electric fields. We were able to obtain from Professor Paul Kintner of Cornell University the electric field data measured by the SIERRA rocket in the auroral zone. We have developed computer codes to confirm that the electric fields are broadband in nature, and also to perform two analyses on the data to determine the degree of intermittency in the fluctuations. Together with the Cornell group, we have submitted an article to Geophysical Research Letter to report the results of these analyses. These results are discussed in Section IV of this report. We expect that similar intermittency analyses can be applied to the electric field measurements in the solar wind.

II. Comparison of Solar Wind Acceleration Mechanisms: Velocity Filtration Effect vs. Ion Cyclotron Resonance

Using the updated version of our global hybrid model, as discussed in Section I, we are able to determine separately the contributions by the velocity filtration effect and ion cyclotron resonance in the driving and acceleration of the fast solar wind. In order to compare these two acceleration mechanisms, we have considered two separate cases, both with the effects of ion cyclotron resonance. However, the treatment of the electrons was different. In the first case, the high-energy (or tail) portion of a Maxwellian electron distribution at the lower boundary was treated with a global kinetic collisional approach. Such an approach enabled us to incorporate the complete kinetic effects, including the velocity filtration effect, due to the suprathermal electrons on the solar wind flow. In the second case, the entire electron population was represented by a Maxwellian distribution throughout the solar wind flow. Thus, the velocity filtration effect was absent in the second solar wind solution.

By recognizing the difference in the results of the two solar wind cases, we were able to determine the contribution due to the velocity filtration effect. A detailed discussion of the results can be found in *Tam and Chang* [2002]. In this report, we briefly compare the two solar wind cases in terms of the outflow speeds of the ions, which are shown in Fig. 1. It is clear that at large heliocentric distances, the inclusion of the kinetic suprathermal electron effects leads to higher ion speeds. However, the difference between the two cases is minimal. The kinetic suprathermal electron effects only lead to a 1.5% increase in the proton speed and a 2.3% increase in the speed of the alpha particles at 1 AU. We note that even under a Maxwellian approximation for the overall electron distributions, the solar wind speed at 1 AU is as high as 650 km/s in the solution. Thus, the available wave power in these calculations seems to be able to drive the solar wind velocity to the high-speed range. For such a strong wave-driven solar wind, it is clear from our results

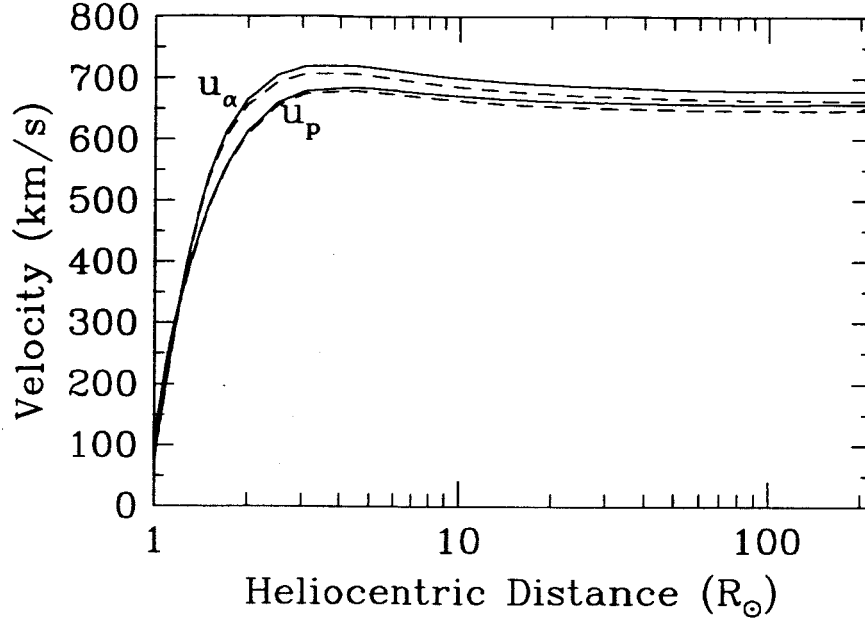


Figure 1. Profiles of the proton (u_p) and alpha particle (u_{α}) outflow speeds. Solid lines: kinetic suprathermal electron effects included; dashed lines: with a Maxwellian approximation for the entire electron distributions.

that velocity filtration effect plays an insignificant role in the driving and acceleration of the solar wind.

We have also extended our calculations to examine the situation of an outflow with a lower wind speed. We arrived at a similar conclusion that the velocity filtration effect is insignificant in the presence of ion cyclotron resonant heating.

III. Effects of Broadband Intermittent Fluctuations

We now briefly discuss our simulation model on the broadband intermittent fluctuations in the aurora. (A detailed discussion can be found in *Chang et al.* [2004] and *Tam and Chang* [2004].) This model can be readily applied to the solar wind, provided the intermittency properties of the turbulent electric field fluctuations is known. For the case of the auroral zone, let us assume the oxygen ions to be test particles with charge q_i and mass m_i . They would respond to the transverse electrostatic electric field fluctuations E_{\perp} near the oxygen gyrofrequency locally according to the Langevin equation:

$$d\mathbf{v}_{\perp} / dt = q_i \mathbf{E}_{\perp} / m_i . \quad (1)$$

To understand the stochastic nature of the Langevin equation, we visualize an ensemble of ions $f(\mathbf{v}_\perp)$ and study its stochastic properties. Assuming that the interaction times among the particles and the local electric field fluctuations are small compared to the global evolution time, we may write within the interaction time scale:

$$f(\mathbf{v}_\perp, t + \Delta t) = \int f(\mathbf{v}_\perp - \Delta \mathbf{v}_\perp, t) P_t(\mathbf{v}_\perp - \Delta \mathbf{v}_\perp, \Delta \mathbf{v}_\perp) d\Delta \mathbf{v}_\perp, \quad (2)$$

where $P_t(\mathbf{v}_\perp - \Delta \mathbf{v}_\perp, \Delta \mathbf{v}_\perp)$ is the normalized transition probability of a particle whose velocity changes from $\mathbf{v}_\perp - \Delta \mathbf{v}_\perp$ to \mathbf{v}_\perp in Δt , and $\Delta \mathbf{v}_\perp$ ranges over all possible magnitudes and transverse directions. At this point, if one applies the standard procedure of the Fokker-Planck formulation, i.e. expanding both sides of Eq. (2) in Taylor series expansions, assuming $O((\Delta \mathbf{v}_\perp)^3)$ terms are of order $(\Delta t)^2$ or higher, and taking the limit $\Delta t \rightarrow 0$, one would then arrive at a standard diffusion equation in the transverse direction. Such an equation would be exact in describing the ion energization processes if the electric field fluctuations were Gaussian.

We shall discuss a general approach for describing the effects of intermittent fluctuations on particle energization processes later. But for the moment, let us assume the Fokker-Planck approach is valid and proceed. Since we have assumed the time scale for the particle-fluctuation interactions is much smaller than the global evolution time of the ion populations, we may then write the steady-state global evolution equation along an auroral field line under the guiding center approximation and neglecting the cross-field drift as [Chang et al., 1986; Retterer et al., 1987; Crew and Chang, 1988]:

$$\frac{\partial}{\partial s} \left[v_\parallel \frac{f}{B_z} \right] + \frac{\partial}{\partial v_\parallel} \left[-\frac{v_\perp^2}{2B_z} \frac{dB_z}{ds} \frac{f}{B_z} \right] + \frac{1}{v_\perp} \frac{\partial}{\partial v_\perp} \left[v_\perp \frac{v_\parallel}{2B_z} \frac{dB_z}{ds} \frac{f}{B_z} \right] = \frac{1}{v_\perp} \frac{\partial}{\partial v_\perp} \left[v_\perp D_\perp \frac{\partial}{\partial v_\perp} \frac{f}{B_z} \right], \quad (3)$$

where v_\parallel, v_\perp are the parallel and perpendicular components of the particle velocity with respect to the field-aligned direction, z . This expression may be interpreted as a convective-diffusion equation for the density of the guiding center ions per unit length of flux tube f/B_z , in the coordinate space of $(s, v_\parallel, v_\perp)$. The perpendicular diffusion coefficient, D_\perp , is given by:

$$D_\perp = (\pi q_i^2 / 2m_i) \langle |E^2|(\Omega_i) \rangle_r, \quad (4)$$

where $\langle |E^2|(\Omega_i) \rangle_r$ is the resonant portion of the average of the square of the transverse electrostatic electric field fluctuations evaluated at the instantaneous gyrofrequency of the ions, Ω_i .

Measurements by polar orbiting satellites indicate that the electric field spectral density Σ follows an approximate power law $\Sigma^{-\alpha}$ in the range of the local oxygen gyrofrequencies, where α is a constant. If we make the additional approximations by assuming that the spectrum observed at the satellite is applicable to all altitudes and choosing the geomagnetic field to scale with the altitude as s^{-3} , we would then expect

$\Sigma(\Omega_i, s)$ to vary as $s^{3\alpha}$. Because we have made some rather restrictive resonance requirements for the fluctuations to interact with the ions, we expect the resonant portion of the average of the square of the transverse electrostatic electric field fluctuations to be only a fraction η of the total measured electric field spectral density. Therefore, we arrive at the following approximate expression for the diffusion coefficient:

$$D_{\perp} = (\eta \pi q_i^2 / 2 m_i^2) \Sigma_0 (s / s_0)^{3\alpha} . \quad (5)$$

We have performed global Monte Carlo simulations for Eqs. (3) and (5) for the conic event discussed by *Retterer et al.* [1987] with $\alpha = 1.7$ and $\Sigma_0 = 1.9 \times 10^{-7} (\text{V/m})^2 \text{ sec/rad}$. The upper left panel of Fig. 2 shows the measured oxygen velocity distribution contours and the upper right panel shows the corresponding calculated contours for $\eta = 1/8$ at the satellite altitude of $s_0 = 2R_E$. Thus, with one eighth of the measured electric field spectral density contributing, the broadband electrostatic fluctuations can adequately generate an oxygen distribution function with the energy and shape comparable to that obtained from observations. This result is comparable to the previously calculated results based on the assumption that the relevant fluctuations were field-aligned propagating electromagnetic ion cyclotron waves [*Chang et al.*, 1986; *Retterer et al.*, 1987; *Crew and Chang*, 1988]. We generally expect the coexistence of nonpropagating transverse electrostatic nonlinear fluctuations and a small fraction of field-aligned propagating waves in the auroral zone. Thus, the ion energization process in the auroral zone is probably due to a combination of both types of fluctuations. The above sample calculations did not include the self-consistent electric field that must be determined in

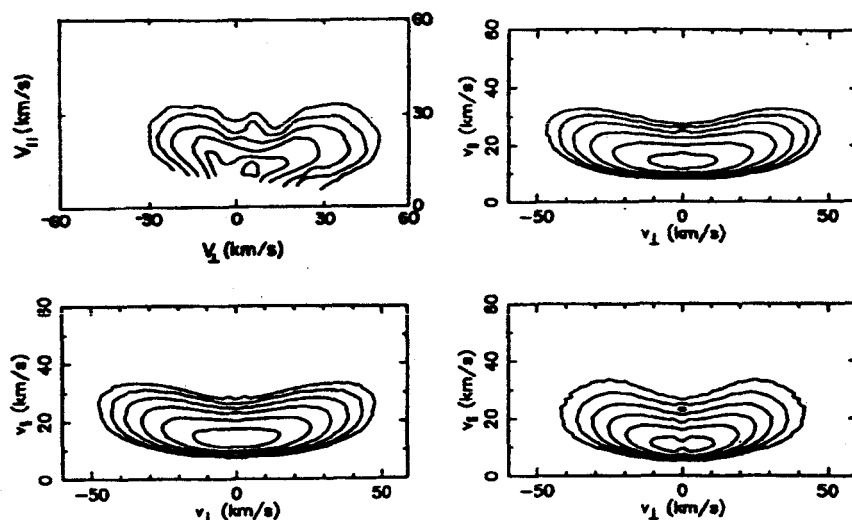


Figure 2. Observed and calculated velocity contour plots for conic event of *Retterer et al.* [1987].

conjunction with the energization of the ions as well as the electrons. However, a self-consistent global evolutionary model can be readily achieved by incorporating the Monte Carlo simulation procedure discussed here into the hybrid technique developed by *Tam et al.* [1995, 1998] originally for the ionospheric polar wind. In terms of simulation techniques, the resulting model would be similar to our global evolutionary model for the solar wind [*Tam and Chang*, 1999a,b; 2001; 2002], which took into account the interactions between the particles and the waves/fluctuations (see Section II).

We now return to the discussion of the effect of intermittency on ion heating. Measurements of the electric field spectral density are generally limited by the response capabilities of the measuring instruments. The faster the instruments can collect data, the more refined the scales of the measurements. We expect the measured spectrum density to exhibit small-scale intermittency behavior. In fact, it is known that fast response measurements generally exhibit strongly intermittent signatures of the fluctuations. In the diffusion approximation, the ion energization process is limited by the amplitude of the second moment of the probability distribution of the fluctuations. This amplitude may become smaller as the scale of measurements is reduced. Thus, in the limit of small scales, the amplitude of the measured spectrum may decrease and thereby requiring a larger value of η to accomplish the same level of energization.

In fact, the diffusion approximation may be inadequate for describing the effects of strong intermittent fluctuations on particle energization. In the approximation, only correlations up to the second order of the fluctuations are included in the formulation of the energization process. Since for intermittent turbulence, the probability distributions of the fluctuations are generally non-Gaussian, the effects of the intermittency can manifest in the higher order correlations beyond the second-order diffusion coefficient. This implies that the higher-order correlations of the velocity fluctuations may be of the order of Δt and therefore cannot be neglected. A more appropriate approach to address such non-Gaussian stochastic processes is to refer directly to the functional equation (2) using the non-Gaussian transition probability or the Langevin equation (1) with the actual intermittent time series of the electric field fluctuations.

We have performed global simulations based on Eq. (2) for non-Gaussian intermittent fluctuations exhibiting the shape suggested by *Castaing et al.* [1990]:

$$\Pi_{\lambda}(\xi) = \frac{1}{2\pi\lambda} \int_0^{\infty} \exp\left(-\frac{\xi^2}{2\sigma'^2}\right) \exp\left(-\frac{\ln^2(\sigma'/\sigma_0)}{2\lambda^2}\right) \frac{d\sigma'}{\sigma'^2}, \quad (6)$$

where ξ represents either the x - or y -component of the dimensionless transverse velocity fluctuations and $\lambda > 0$ is parameter that characterizes the intermittency. We set $\ln \sigma_0 = -\lambda^2$, to ensure the variance equal to unity. For $\lambda = 0$, Eq. (6) reduces to a Gaussian distribution. As λ increases, the degree of intermittency increases. The lower left panel of Fig. 2 shows the contours calculated for $\lambda = 1$ with $\eta = 1/8$. For this case, the degree of intermittency is not strong enough to significantly affect the value of η . But with strong intermittent fluctuations ($\lambda = 2$, lower right panel of Fig. 2), a value of η equal to $1/5$ is required to adequately generate the ion conic to observed energies.

IV. Intermittency Analyses of Electric Field Fluctuations

From the results of our simulations, we understand how the intermittency of the electric field fluctuations can affect the ion energization processes in a plasma outflow. Thus, it is important for us to determine the degree of intermittency for these fluctuations. That would enable us to use experimentally relevant information in our simulation model. Very recently, the electric field data measured by the SIERRA (Sounding of the Ion Energization Region: Resolving Ambiguities) rocket in the auroral zone has become available to us. We are motivated to analyze these data for intermittency. We have developed computer codes for two intermittency analyses, based on the method of probability distribution functions (PDF) and the technique of wavelet transforms and local intermittency measures (LIM). Using our codes, we have successfully demonstrated that the auroral electric field fluctuations are intermittent, and determined their degree of intermittency, as will be discussed below. We expect that similar intermittency analyses can be applied to the electric field measurements in the solar wind.

The electric field instrument of SIERRA and the measurement of the data were discussed in *Tam et al.* [2004]. The data used in our studies are a time series of an electric field component that is perpendicular to the local geomagnetic field. The component is approximately in the geographical north direction, and for this reason, is labeled E_{north} . We analyze the time series for the interval when the altitude of SIERRA was between 700 km and its apogee (735 km). The top panel of Fig. 3 shows the E_{north} fluctuations at the interval. Notice that the fluctuations are broadband in nature, with power-law spectral density covering the extremely low-frequency range (3 to 200 Hz), as indicated in the lower panel of Fig. 3. Such a spectrum suggests that the fluctuations are typical broadband extremely low-frequency (BB-ELF) electric fields,

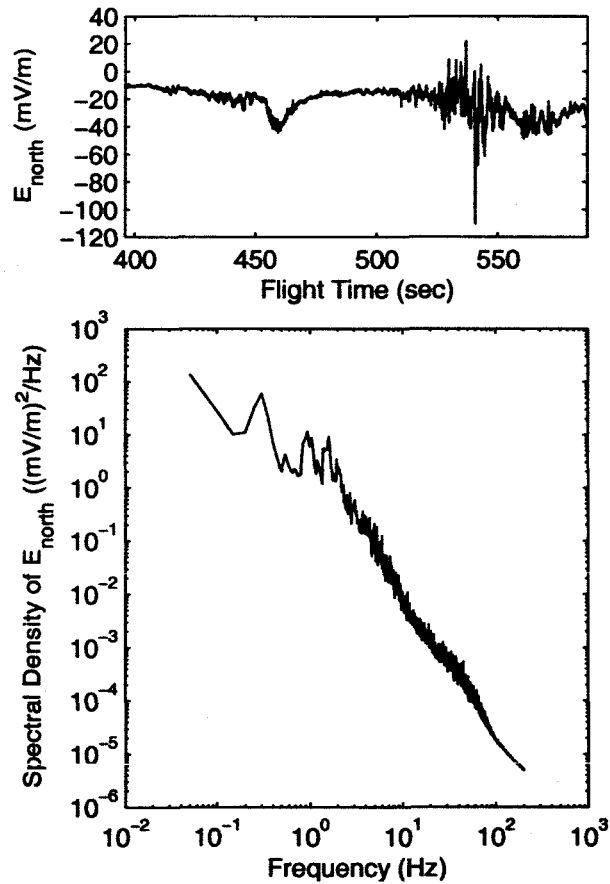


Figure 3. Top panel: Plot of electric field component E_{north} versus the flight time of the SIERRA rocket for the duration when the rocket was above 700 km altitude. Bottom panel: Average spectral density of E_{north} over the duration.

which have been frequently observed at different altitudes of the auroral zone. We have also taken the average spectral density of the fluctuations over different sub-intervals, and found similar power laws in the extremely low-frequency range for all those time ranges. Thus, the results are quite robust.

Below, we shall discuss the results of our analyses of these typical auroral electric field fluctuations based on the techniques of probability distribution functions (PDF), wavelet analyses and local intermittency measures (LIM).

IV.1 Probability Distribution Functions (PDF)

To examine the electric field fluctuations for intermittency, we first study how much their statistics deviate from those of Gaussianity. The amount of the deviation indicates the degree of intermittency. For a fluctuating field X , we generate the PDF $P(\delta X, \tau)$ of $\delta X \equiv X(t + \tau) - X(t)$ for different values of τ over a certain range of time t . It is expected that the range of δX is wider for larger values of τ . Thus, in order to compare the deviation of the PDF from Gaussianity at different scales, it is useful to consider their normalized distribution instead. We normalize the PDF by $\sqrt{\langle (\delta X)^2 \rangle}$, the root-mean-square value of δX , which we denote as $\sigma(\tau)$. The normalized PDF becomes:

$$P_*(\delta X / \sigma, \tau) = \sigma P(\delta X, \tau), \quad (7)$$

whose variance is always unity, independent of the scale τ . Based on the fluctuations shown in the top panel of Fig. 3, we have generated normalized PDF P_* with a few different values of τ . Figure 4 shows the distributions P_* at three different scales for $X = E_{\text{north}}$ (top panel) and E_{north}^2 (bottom panel). As indicated in the figure, we find that for either E_{north} and E_{north}^2 , the corresponding P_* does not differ by much at different scales, for τ up to about 1 second. Also, the normalized PDF deviates significantly from a Gaussian distribution in both panels, indicating intermittency in the electric field fluctuations. Recently, *Hnat et al.* [2002] has introduced a mono-power scaling relation of the form $P(\delta X, \tau) = \tau^{-\gamma} P_*(\delta X \tau^{-\gamma}, \tau)$. We note that the mono-power scaling condition implies $\sigma \sim \tau^\gamma$ and the collapse of P_* onto a single curve, and *vice versa*. We find that $\sigma \sim \tau^\gamma$ holds true in our data for scales up to about 200 ms, with $\gamma = 1.60$ and 1.70 for $X = E_{\text{north}}$ and E_{north}^2 respectively. Thus, the mono-power scaling relation should also hold true for the data within the same scale range.

To characterize the intermittency, we try to fit the normalized PDF with Eq. (6), the Castaing distribution [Castaing et al., 1990]. Recall that $\lambda > 0$ is the parameter that characterizes the intermittency of the distribution. The degree of intermittency increases with λ . For the distribution to have a variance of unity, it is necessary that $\ln \alpha_0 = -\lambda^2$. As shown in Fig. 4, P_* can be approximately fitted with Castaing distributions of $\lambda = 0.87$ for E_{north} and $\lambda = 1.21$ for E_{north}^2 .

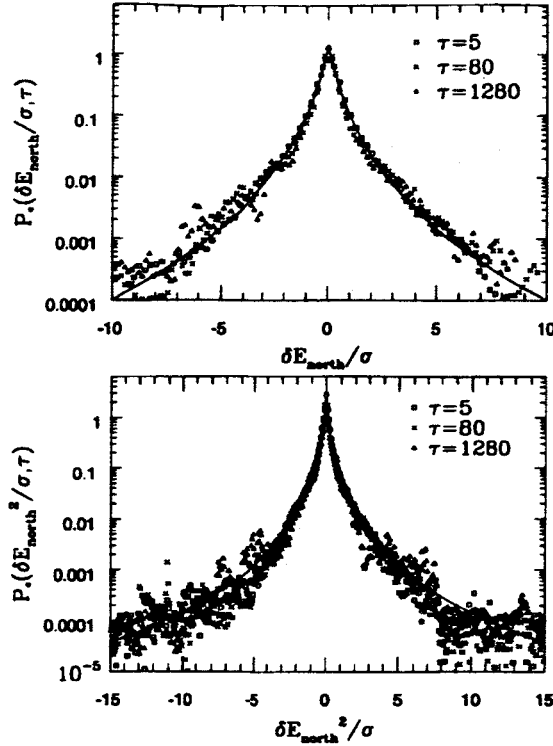


Figure 4. Normalized PDF $P_*(\delta X / \sigma, \tau)$ for $X = E_{north}$ (top) and E_{north}^2 (bottom) at $\tau = 5, 80$ and 1280 ms. The solid lines correspond to the normalized Castaing distribution with $\lambda = 0.87$ (top) and 1.21 (bottom).

IV.2 Wavelet Analyses and Local Intermittency Measures

As the electric field fluctuations are intermittent, we identify the time at which the power of the fluctuations at various scales concentrates. With such information, we can determine the intermittency of the fluctuations at these scales. This can be accomplished by the technique of Local Intermittency Measures (LIM) using wavelet transforms. A wavelet transform is generally composed of modes which are square integrable localized functions that are capable of unfolding fluctuating fields into time (or space) and scales [Farge, 1992]. The power of the fluctuations at different time and scales is characterized by a set of coefficients of the transform. We apply the Haar wavelet transform [Bruno *et al.*, 2001] to find $W_s(t)$, the coefficients of the wavelets for E_{north} at various scales s and time t . The power of the wavelets $|W_s(t)|^2$ is shown in Fig. 5a. Note that as evident in the figure, the strong fluctuations around $t = 540$ (see Fig. 3) contribute to the high power of the wavelets in this time range. The power of the fluctuations mainly concentrates at the scales of 320 ms or larger.

To study the intermittency of the fluctuations at different scales, we first define $LIM(s, t) \equiv |W_s(t)|^2 / \langle |W_s(t)|^2 \rangle_t$, where $\langle \dots \rangle_t$ denotes the averaging over time. LIM measures the relative power among wavelets of the same scales throughout the time

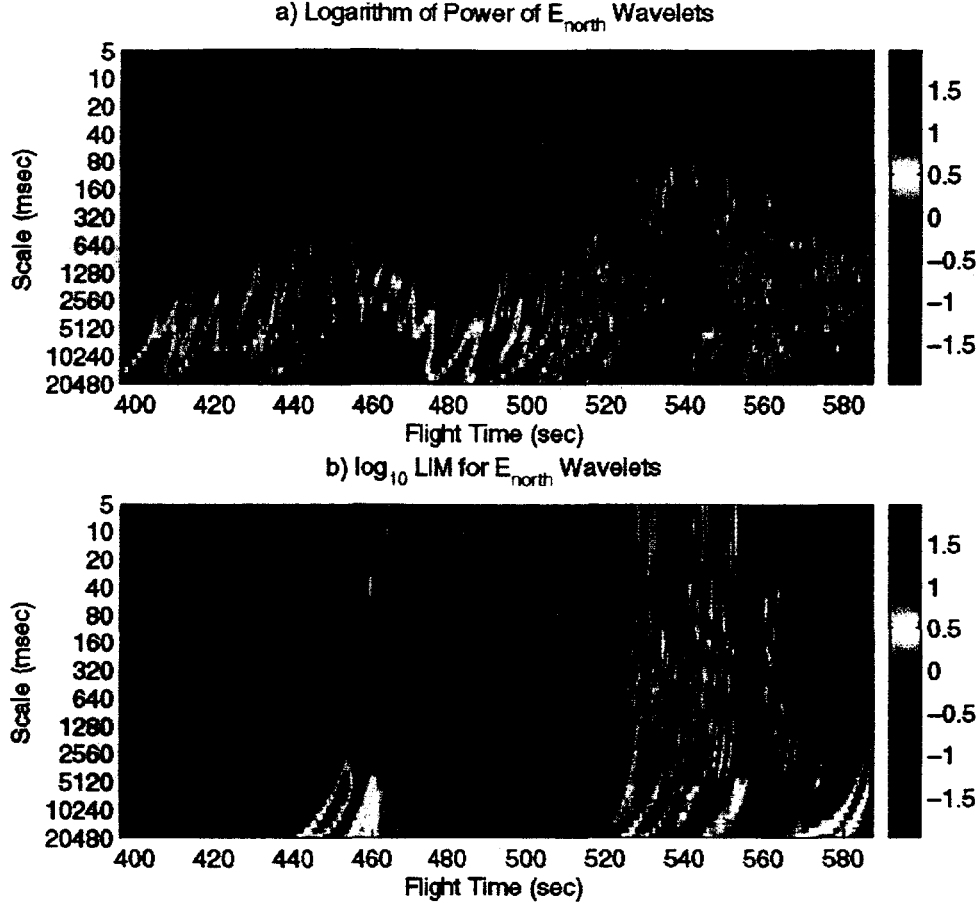


Figure 5. (a) Power of the wavelets for E_{north} ; (b) LIM for the wavelets.

domain. For any given scale, LIM averages to 1 over time. From the results shown in Fig. 5b, although there is strong wavelet power near $t = 540$ at the scales larger than 320 ms (see Fig. 5a), the LIM in this time range is large only for scales between 320 and 5120 ms, but considerably smaller for the larger scales. This is because at other time, there is also strong wavelet power at these larger scales. In other words, the power of the wavelets at these scales is more uniform in time compared with the smaller scales. In fact, for a given scale, intermittency is not measured by its overall wavelet power, but is characterized by the degree of non-uniformity of the wavelet power (or LIM) in time; the less uniform the LIM , the higher degree the intermittency. A direct measure of the degree of intermittency is $Flatness(s) = \langle [LIM(s,t)]^2 \rangle$, [Meneveau, 1991]. We note that the flatness for Gaussian fluctuations equals 3. Therefore, flatness larger than 3 would indicate that the fluctuations are intermittent. The flatness for E_{north} at various scales are shown in Fig. 6. Except at the largest scales, the flatness for E_{north} is generally larger

than 3. The flatness is generally higher for smaller scales, indicating that the degree of intermittency for the electric field fluctuations varies inversely with the time scale. For time scales of a few milliseconds, the flatness increases to several thousands.

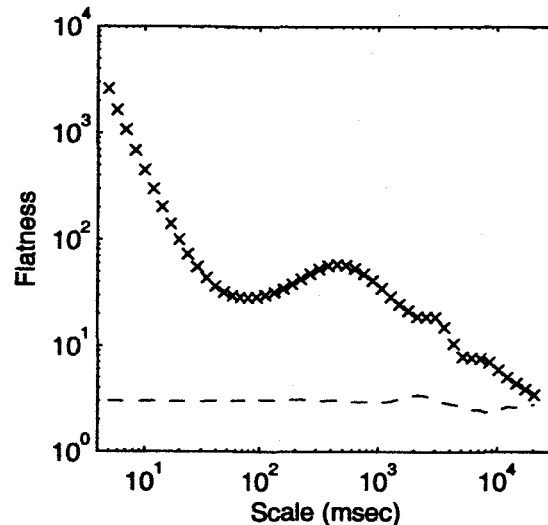


Figure 6. Plot of the flatness for the wavelets versus scale: symbols “x” for E_{north} ; and for comparison, dashed line for Gaussian fluctuations.

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- Tam, S. W. Y., T. Chang, P. M. Kintner, and E. Klatt, Intermittency analyses on the SIERRA measurements of the electric field fluctuations in the auroral zone, submitted to *Geophys. Res. Lett.*, 2004.

V. Recent Publications Relevant to the Grant

- Tam, S. W. Y., T. Chang, P. M. Kintner, and E. Klatt, Intermittency analyses on the SIERRA measurements of the electric field fluctuations in the auroral zone, submitted to *Geophys. Res. Lett.*, 2004.
- Tam, S. W. Y., and T. Chang, Energization of ions by bimodal intermittent fluctuations, in *Multiscale Coupling of Sun-Earth Processes*, eds. A. T. Y. Lui, Y. Kamide, and G. Consolini, in press, 2004.
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- Tam, S. W. Y., and T. Chang, Comparison of the effects of wave-particle interactions and the kinetic suprathermal electron population on the acceleration of the solar wind, *Astron. & Astrophys.*, 395, 1001, 2002.

VI. Invited Lectures

- Conference on Sun-Earth Connections: Multiscale Coupling of Sun-Earth Processes in Kona, Hawaii, February 2004
- Kanazawa University, Kanazawa, Japan, February 2004
- Per Bak Memorial Session on Nonlinear Processes in Space Plasmas, Joint EGS-AGU-EUG Assembly, Nice, France, 2003.
- Session on Solar System Plasmas, Joint EGS-AGU-EUG Assembly, Nice, France, 2003.
- Symposium on Complexity in Space Plasma Processes, IUGG Assembly, Sapporo, Japan, 2003.
- Second International Astrophysical Conference on Waves and Turbulence in Interplanetary and Astrophysical Media, Palm Springs, CA, 2003
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